# Attachment "7" (Part 2 of 2)

in principle to that of Fowler and of Osborne, and the excellent fits to the extensive calculations of electron beam energy dissipation reported by Spencer,[44] together with a wide range of energy dissipation measurements, provide strong evidence for the essential correctness of the treatment. We hope that further Monte Carlo calculations can be done in which $\epsilon_v(r)$ is evaluated for the region of emulsion about midway between the two surfaces, for the resulting curves would be directly comparable with experimental observations.

Despite quantitative differences in the details of the energy deposition curves, we believe that the two models that use the exact Mott cross section allow us to draw the same qualitative conclusion: The small distant energy deposition in the emulsion is satisfactorily accounted for by the highly relativistic superheavy element with $Z/\beta \approx 110$ to 114, by the fast antinucleus, and by the slow, supermassive particle.

### B. Compatibility of the three candidates with the Lexan data

Hagstrom has pointed out[14] that a fast antinucleus with $Z/\beta \approx -114$ not only fits the emulsion data but fits the Lexan data better than would a nucleus with the same velocity and opposite charge. Because of the lower Mott cross section, $dE/dx$ for the antinucleus would be considerably less than for the nucleus, making it a more penetrating particle with a smaller loss of speed in passing through the stack. For $|Z|/\beta \approx 114$ and $\beta > 0.6$ Hagstrom calculated that the stopping power of an antinucleus would be 15% to 25% lower than the stopping power of its charge conjugate.[14] This result can easily be verified using the analytic expression of Ahlen.[46] This difference in $dE/dx$ gives rise to an etch rate vs range curve with reduced positive slope. For an antinucleus in the pertinent charge regime $-96 \lesssim Z \lesssim -76$ the etch rate vs range curve is similar to that of the positive nucleus with the same initial $|Z|/\beta$ and about three charges higher. (Note that the etch rate at a given $|Z|/\beta$ is the same for $Z$ and $\bar{Z}$; it is only the rate of increase of etch rate with depth that differs for $Z$ and $\bar{Z}$.) Thus, if in Table II we admit that positive nuclei, with possible fragmentations allowed for, with initial charges between ~76 and ~96 can fit the Lexan data, then antinuclei with the same fragmentation sequence and charges $-73$ to $-93$ would have comparable fits, and antinuclei with charges $-76$ to $-96$ would fit the data better.

Hagstrom has argued[14] that fragmentation with small loss of charge in a peripheral collision would be more likely for an antinucleus than for a positive nucleus. Thus, an antinucleus with $|Z| \gtrsim 76$ and average $Z/\beta = -114$, possibly fragmenting, is compatible with all the data in our Sioux City experiment. We will comment on its compatibility with negative searches by previous experimenters in Sec. VIII.

All of the track-structure models agree that the distant energy deposition by a *slow* particle with $|Z|/\beta \approx 114$ would be small enough to be compatible with the visual and photographic evidence. The best estimate of the necessary velocity is $\beta \approx 0.4$. But we have seen in Sec. V that the rate of change of etch rate through the Lexan stack would be ridiculously high for a nucleus with any ratio of $Z/A$ compatible with particle stability and $\beta$ as low as 0.6. Only if the mass were enormously large would the rate of slowing, $d\beta/dx$, be low enough to give an etch rate vs range curve compatible with the Lexan data. It is easy to see approximately how large the mass of the slow particle would have to be if we take $dE/dx$ as approximately proportional to $Z^2/\beta^2$ and write

$$\frac{dE}{dx} = \frac{dE}{d\gamma}\frac{d\gamma}{d\beta}\frac{d\beta}{dx} = \frac{\beta_i A_i m_p c^2}{(1-\beta_i^2)^{3/2}}\frac{d\beta_i}{dx} \approx C\frac{Z_i^2}{\beta_i^2} = (114)^2 C\,. \tag{34}$$

As an example, $d\beta/dx$ for a supermassive particle with $\beta = 0.4$ and $Z/\beta = 114$ will equal $d\beta/dx$ for a nucleus with $Z = 92$, $A = 238$, $\beta = 0.81$ (such that $Z/\beta = 114$) provided the supermassive particle has a mass of ~1840 amu. However, the fit for a uranium nucleus is unacceptably poor unless it fragments once. If the slow particle is to give an acceptable fit to the data without fragmenting, it must have $d\beta/dx$ comparable to that for a hypothetical nucleus with $Z \approx 108$, $\beta \approx 0.95$. Its mass must then be ~56 times greater than the mass of the nucleus with $Z = 108$, or about 16 000 amu, and its mass to charge ratio would be ~350. Hypothetical charged particles with huge mass and huge $A/Z$ ratio have been discussed in several contexts in the literature.[47-50] We will include them in our discussion in Sec. VIII.

Assuming the applicability of the restricted-energy-loss model of track formation in Lexan, Ahlen showed[12] that a monopole of charge $g = 137e$ and low speed, $\beta \approx 0.3$, could account for the Lexan data, provided its mass were sufficiently great to give a nearly zero value of $d\beta/dx$ and thus a nearly zero value of $dV/dR$. The slope $dV/dR$ would be small enough to be compatible with the Lexan data if, for $\beta = 0.3$, the mass were at least 3400 amu. Kinematics alone ensures that for $\beta \approx 0.3$ the distant energy deposition by a monopole with $g = 137e$ would be quite low, perhaps even compatible with the visual and photographic data for the 200-$\mu m$ emulsion. We will discuss the difficulties of the

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monopole interpretation in Sec. VIII.

A hypothetical superheavy nucleus, $Z\approx 110$ to 114, $\beta\approx 1$, gives an excellent fit to the Lexan data. In discussing the response of Lexan, we showed that either Eq. (4) (with $K\approx 62$) or Eq. (5) gave an adequate representation of the energy deposition at small radial distances. The last two rows of Table I show the charges predicted by these two models, along with the charge predicted by the unsatisfactory model in which restricted energy loss is used as the criterion for track formation. An Fe nucleus with a speed $\beta=0.22$ has $Z^*/\beta=114$ and an etch rate identical to the average rate for the monopole candidate. If the particle were a nucleus with $\beta\approx 1$, the two acceptable models would predict $Z=114$ and 109; if it were a nucleus with $\beta\approx 0.98$, the two models would predict $Z=112$ and 108. These values are quite consistent with the range of charges of hypothetical superheavy nuclides calculated to have long half-lives. We regard a nucleus with $Z=110$ to 114, $\beta\gtrsim 0.99$, and $Z/\beta\approx 110$ to 115 as compatible with the etch rate data in Lexan and with the distant energy deposition in emulsion. We will include this hypothetical superheavy nucleus in our discussion in Sec. VIII.

A hypothetical particle with $Z/\beta\approx 114$ and a diffuse charge distribution extending to a radial distance of ~$10^2$ F could in principle account for the small number of high-energy δ rays in emulsion. We will not consider such a hypothetical particle because we want to focus discussion in this paper on particles that not only fit the data but have been predicted to exist.

## VIII. DISCUSSION

Table IV summarizes the status of the evidence. The first five columns, which relate to our own experiment, simply recapitulate what has been said in Secs. IV through VII. Assuming that an entry represents a positive observation of a particular particle, column 6 indicates whether it constitutes a serious discrepancy with searches by other experimenters.

### A. Was the event a normal nucleus?

The entries in the first three rows of Table IV refer to normal nuclei known or expected to exist in the cosmic rays ($Z\leqslant 96$). If we accept the constraint from the Lexan data that $|Z/\beta|\approx 110$ to 115, then nuclei with $\beta\lesssim 0.6$ fail to fit the Lexan data and nuclei with $\beta>0.5$ fail to fit the emulsion data. There is thus no velocity for which a normal nucleus would fit both the Lexan data and the emulsion data. Even if we were to admit the possibility that the nucleus underwent an abnormally large number of properly spaced nuclear fragmentations

TABLE IV. Compatibility of particles with $|Z|/\beta\approx 114$ with the data and with other searches.

| Type of particle | Properties | Lexan data | Data from 3 emulsions | Lexan + emulsions | Discrepancy with other searches? | Overall compatibility |
|---|---|---|---|---|---|---|
| nucleus | $0.6<\beta\lesssim 0.84$, $Z/\beta=+114$ | acceptable, but see Table I | unacceptable | unacceptable | none | no |
| nucleus | $0.5<\beta\lesssim 0.6$, $Z/\beta=+114$ | unacceptable $CL<10^{-18}$ | acceptable if $\beta\approx 0.5$ | unacceptable | none | no |
| nucleus | $0.4\leqslant\beta\lesssim 0.5$, $Z/\beta=+114$ | unacceptable $CL<10^{-18}$ | acceptable | unacceptable | none | no |
| antinucleus | $76\lesssim\|Z\|\lesssim 96$, $Z/\beta=-114$ | acceptable | acceptable | acceptable | Indirect negative evidence | yes |
| supermassive | $\beta\approx 0.4$, $Z/\beta=+114$, $M>10^{3}$–$10^{4}$ amu | acceptable | acceptable | acceptable | none | yes |
| magnetic monopole | $\beta\approx 0.4$, $g=137e$ $M>10^{3}$ amu | unacceptable | acceptable | unacceptable | large discrepancy unless $M\gtrsim 10^{11}$ amu | no |
| nucleus | $\beta\geqslant 0.99$, $Z\approx 110$ | acceptable | acceptable | acceptable | none | yes |

or attached an unusually large number of atomic electrons so as to match the Lexan data, it would, in order to penetrate the Lexan stack, have too high a velocity to fit the emulsion data.

We now consider whether unexpectedly large systematic errors might allow a normal nucleus to fit both the Lexan data and the emulsion data. Again accepting the constraint from the Lexan data that $|Z/\beta| \approx 110$ to 115, we would have to make the *ad hoc* hypothesis of some unexplained failure in response of all three emulsions. The statistics of $\delta$-ray production along the track in the two emulsions are poorer than for the track in the thick emulsion, and fewer events have been studied in the thin emulsions than in the thick emulsion. Nevertheless, using the fluctuations of the data in Fig. 17 as a measure of $\delta$-ray statistics and of reproducibility of response of the thin emulsions makes it appear quite unlikely that the event was a normal nucleus. Consideration of the visual and photographic data for the thick emulsion, together with the AMID data for the thin emulsions, makes the case against a normal nucleus very much stronger than if data were available only for the thick emulsion or the two thin emulsions.

Finally, we consider the strength of the constraint from the Lexan data that $|Z/\beta| \approx 110$ to 115. Referring to the last two rows of Table I, we see that an ultrarelativistic nucleus with $Z \approx 89$ to 90, $\beta \approx 0.98$ to 1, and $Z^*/\beta \approx 89$ to 92 could produce the same track etch rate as an Fe nucleus with $Z^*/\beta \approx 114$ if the restricted energy loss model [Eq. (2)] were an adequate representation of the energy deposition at small radial distances. The distant energy deposition by such an ultrarelativistic nucleus would probably be compatible with the track structure in the emulsion. However, the evidence in Table I shows that the restricted-energy-loss model does not fit the available data. Lest one think that a discrepancy of one charge at $Z = 10$ is not significant, we point out that, because the track etch rate increases roughly as the fourth or fifth power of $Z$, a 10% error in charge amounts to at least a 50% error in etch rate. At $Z \approx 77$ to 92 the discrepancy is about ten charges. Thus, both the low- and high-charge measurements of standard particles summarized in Table I are incompatible with a restricted-energy-loss model. By using Eq. (4) instead of the restricted-energy-loss model and arbitrarily dropping the value of $K$ from 62 to about 15 or 20, one could somewhat reduce the discrepancy with the low- and high-charge measurements in Table I and allow a nucleus with $Z = 96$ and $\beta \approx 1$ to produce a track like that of an Fe nucleus with $Z^*/\beta = 114$. With this choice of $K$, the cosmic-ray abundance peak would move to $Z \approx 70$ instead of 67, and the ions with $Z = 10$ would have charges calculated to be $Z \approx 10.7$ instead of 11. Even this "optimum" choice of energy deposition equation could, we believe, be reconciled with the data in Table I only by rejecting the astrophysical evidence for $r$-process nucleosynthesis and an end of the charge spectrum at $Z \approx 92$ to 96. Choosing a value of $K$ between 20 and 62 does not help, because there is no known long-lived nuclide with $Z > 96$.

It is true that we have no direct measurement of the velocity dependence of the track etch rate at very high Lorentz factor. One might hypothesize that at high $\gamma$ the etch rate might increase enough that a nucleus with $Z \approx 90$ to 96 could mimic a nucleus with low $\gamma$ and $Z/\beta \approx 114$. However, the density effect is known to prevent an increase of the energy loss due to distant collisions at high $\gamma$ in a condensed medium, whereas it does not affect the close collisions. Regardless of whether Eq. (2), (4), or (5) represents track formation in Lexan better, it is clear that the density effect will prevent a relativistic rise in the etch rate because etched tracks result from energy deposited at small radial distances.

We conclude that a normal nucleus cannot account for the event unless we invoke large downward fluctuations in the distant energy deposition or in the response of all three emulsions.

### B. Was the event a fast, heavy antinucleus?

As row 4 of Table IV points out, an antinucleus with suitable charge, velocity, and possible fragmentations is compatible with the data in Lexan and in the emulsions. We consider now the theoretical expectations, previous searches, and indirect negative astrophysical evidence for antinuclei in nature. The positron, the antiproton, and numerous other antiparticles up to anti-$^3$He in mass have been produced in accelerators, and even the most conservative physicists would agree that highly charged antinuclei are not excluded by the laws of physics. In fact, the symmetry between particles and their charge-conjugate antiparticles is quite well established, whereas the symmetry between electric and magnetic charge remains only a theoretical possibility.

The question of whether the present universe could be baryon-symmetric is still under debate. Of the theoretical models purporting to explain how large-scale regions of matter and antimatter could separate and survive complete annihilation, the one by Omnès and co-workers[51] has been developed the most quantitatively and has been discussed the most in recent years. Our views and those of a number of astrophysicists are that, though various aspects of the model have been criticized,[52] it describes a scenario that might have occurred, and

that the question of whether large-scale regions of antimatter exist will have to be answered experimentally.

$\gamma$-ray measurements from satellites and balloons provide upper limits on the rate of annihilation of matter and antimatter in different regions of space.[52] They suggest that there is very little antimatter in the intergalactic medium, in neighboring galaxies, or in gas in our Galaxy, and that the fraction of antistars in our Galaxy is likely to be less than $\sim 10^{-4}$. However, Stecker[53] has argued that the best explanation of the shape of the energy spectrum of diffuse $\gamma$ rays is that they are the products of annihilation integrated back in time to red shifts of ~100. Further, Sofia and Van Horn[54] and Vincent and Thompson[55] have proposed that the much studied $\gamma$-ray bursts from space are caused by annihilation of antimatter.

The above evidence is indirect. Measurement of the sign of the nuclear charge of cosmic rays would be direct. Searches with superconducting magnets have yielded only null results.[52] The upper limit on the fractional flux of antinuclei in the cosmic rays is $\sim 10^{-5}$ to $\sim 10^{-4}$ for light antinuclei and $\sim 10^{-3}$ to $\sim 10^{-2}$ for anti-iron. There is, however, no direct negative experimental evidence against the interpretation of our event as an antinucleus with $|Z| \gtrsim 76$, because the total collecting power of all such experiments is about four orders of magnitude smaller than that of Lexan and emulsion experiments. Furthermore, almost all of the previous searching was done at high rigidity, whereas if our particle was an antinucleus it had a rather low rigidity. Even if one assumes locally identical charge spectra and rigidity spectra for positive and negative nuclei, a fractional flux of $10^{-5}$ to $10^{-4}$ is not seriously discordant with our observation of one possible antinucleus. A total of $\sim 10^2$ particles with $|Z| \geq 60$ and $\beta \gtrsim 0.6$ have been identified with a Lexan stack and have had their distant energy deposition measured with emulsion. To have found one antinucleus out of $10^2$ normal nuclei would be regarded as lucky but not statistically incompatible with an average ratio a few hundred times lower.

### C. Was the event a slow, supermassive particle?

Row 5 of Table IV indicates that a hypothetical particle with a huge ratio of $A/Z$ could fit the data and does not conflict with previous searches for such particles.

Yock[47] has proposed that hadrons are composed of heavy, highly electrically charged "subnucleons," of which the heaviest stable one would have a mass of order 200 to 2000 amu and electric charge of order $40e$. In Sec. VII we showed that if our event was a slow particle with $\beta = 0.4$ and $Z/\beta = +114$, its charge would be $Z \approx 46$ and its mass would be $\gtrsim 1840$ amu. These numbers are consistent with those for Yock's heaviest subnucleon.

Lipkin[56] has noted that if free quarks exist[57] they should have an attractive interaction with nucleons and should form stable quark-nuclei that might have very large values of $Z$ and $A$. The quark-nucleus with greatest binding energy per nucleon would have a $Z$ greater than that of iron, the ordinary nucleus with greatest binding energy per nucleon, and $A/Z$ might be considerably larger than for ordinary nuclei.

Several theorists[48-50] have discussed the possibility of an abnormally dense phase of nuclear matter with peculiar properties. The range of masses, charges, and $A/Z$ ratios contemplated in one or another of these papers overlaps with the values required of our particle.

There is still another hypothetical particle to consider. Hawking[58] has suggested that a large number of small black holes, of mass $10^{-5}$ g upwards, may have been formed as a result of fluctuations in the early universe. The lower mass limit is a consequence of quantum gravitational effects, which limit the minimum Schwarzschild radius to about the Planck length. Given that the average density of the universe is no greater than $\sim 10^{-29}$ g/cm$^3$, the flux of black holes of mass $\geq 10^{-5}$ g cannot exceed $\sim 10^{-2}$/m$^2$yr. The probability of such a black hole striking one of our detectors is thus small but not impossibly small. However, Hawking[59] has shown that a charged black hole would spontaneously lose charge by pair creation and that even an uncharged black hole would lose mass rapidly by this process if its mass were less than $\sim 10^{15}$ g. Thus, a small black hole would be essentially neutral and could not produce detectable effects in Lexan or emulsion.

The collecting power of Lexan/emulsion stacks so far exceeds that of all other detectors in balloons or satellites that the failure of other groups to detect a supermassive particle such as Yock's subnucleon, Lipkin's quark-nucleus, or an abnormally dense particle at high altitude is perfectly natural. We must consider also the possibility that a slow, supermassive particle might reach sea level without a destructive interaction in the atmosphere. A particle with initial velocity $\sim 0.4c$ and charge $46e$ would reach sea level at vertical incidence if its mass exceeded $\sim 2 \times 10^5$ amu and if it interacted only by ionization loss. Such a slow particle would not be accompanied by an electromagnetic shower and could be detected at sea level or greater depths only by a detector sensitive to a single particle of extraordinarily high ionization rate. It would probably have gone unnoticed in one of the giant emulsion or x-ray film arrays exposed

at mountain stations on various continents but would have produced a detectable track in a sea-level Lexan array[60] exposed at the General Electric Research Laboratory with a collecting power of ~20 m$^2$yr. It might also be detected in a large electric detector. At sea level several such detectors have been installed, following our first paper on the monopole candidate. No results have yet been published. If its mass were as great as ~$10^8$ amu it might penetrate deep enough underground to produce a large signal in the neutrino detector of Reines and co-workers.[61] Their accumulated total number of events with unusually large signals corresponds to a flux no greater than ~0.02 m$^{-2}$yr$^{-1}$ at a depth of $10^6$ g/cm$^2$. Neither this limit nor that computed from the sea-level Lexan experiment poses a compelling conflict with our observation of a single event. Highly ionizing, electrically charged supermassive particles at a flux of ~1 m$^{-2}$yr$^{-1}$ would appear to have no observable large-scale astrophysical consequences unless their total mass were so great as to contribute significantly to the expansion rate of the universe. This limit, ~$10^{-7}$ g per particle, seems so high as to be uninteresting. We conclude that the interpretation of our event as a slow, electrically charged particle of mass >$10^3$–$10^4$ amu is not ruled out by theory, previous searches, or astrophysical affects.

### D. Was the event a monopole?

Row 6 of Table IV summarizes the case against a monopole. Ahlen's analysis showed that a slow monopole would have a lower $dE/dx$ and a lower restricted energy loss than a fast monopole because of the existence of a velocity-dependent logarithmic term. However, the restricted-energy-loss model does not fit data for heavy charged particles and the two models that do fit the data, Eqs. (4) and (5), would have either a very weak or nonexistent velocity dependence when modified to apply to magnetic monopoles. We regard a slow monopole as incompatible with the Lexan data. At a speed $\beta \approx 0.4$ the distant energy deposition by a monopole would be compatible with the emulsion data.

The observation of one monopole in experiments with a total collecting power of ~1 m$^2$yr would constitute a very large discrepancy with previous negative searches and with astrophysical effects unless its mass were enormous. Ross[62] has summarized the negative searches, several of which had a collecting power ~$10^6$ times greater than that of the Lexan/emulsion experiments. The searches for ancient tracks in mica or obsidian[63] were aimed at relativistic monopoles and might not be sensitive to slow monopoles because the thresholds for track-recording in mica and obsidian, though poorly known, are thought to be marginally able to detect a particle with $Z/\beta \approx 137$ but might not be able to detect a particle like ours, with $Z/\beta \approx 114$. Experiments that used strong magnets to extract monopoles from ferromagnetic ocean sediments and direct them through a plastic track detector[64] or electronic detectors[65] would have given null results if the monopoles had masses greater than ~$10^4$ amu because they would have missed the detectors. The collecting power of the lunar experiments of Alvarez and co-workers[66] decreases rapidly for monopoles of large mass, which would bury themselves at great depths instead of in the shallow subsurface soil. The maximum available center-of-mass energy at the Fermilab and CERN Intersecting Storage Rings accelerators is inadequate to produce monopoles with mass greater than 14 and 30 amu respectively. Searches at those accelerators have given null results.[67]

Through their interactions with the 2.7 °K background radiation and with galactic magnetic fields, monopoles might have profound astrophysical effects. Osborne[68] has obtained very restrictive limits on fluxes of monopoles of either galactic or extragalactic origin by considering energetic photons that would originate in inverse Compton scattering of 2.7 °K background photons on energetic monopoles. For a monopole mass greater than ~$10^6$ amu these limits are no longer restrictive. Parker[69] has shown that the stability of the interstellar magnetic field limits the flux of monopoles residing in the Galaxy to ~$3\times10^{-5}$ m$^{-2}$yr$^{-1}$; a higher flux would extract energy from the field faster than it could be replenished. The flux of primordial extragalactic monopoles of sufficiently high energy ($\gtrsim 10^{11}$ GeV) is not restricted by the above argument, because they would give energy to the magnetic fields in a galaxy through which they passed as often as they would extract energy.[70] In order to have $\beta \approx 0.4$, such monopoles must have mass $\gtrsim 10^{11}$ amu. Thus, to reconcile the detection of a monopole with a collecting power of only ~1 m$^2$yr with both astrophysical constraints and previous negative searches without invoking a huge statistical fluctuation, the monopole must have a mass $\gtrsim 10^{11}$ amu. Such a large mass is not excluded by theory but is perhaps offensive.

We conclude that there is no justification for referring to the particle as a "monopole candidate."

### E. Was the event a superheavy nucleus ($Z \approx 110$ to 114)?

Of the three candidates in Table IV that give more or less acceptable fits to all the data, the highly relativistic, superheavy nucleus can be ac-

commodated most comfortably within the framework of theory, previous experiments, and astrophysical effects. There is general agreement[71] among nuclear structure theorists that shell closures at $Z=114$, $N=184$, will give rise to an island of increased stability around $Z=114$, $A=298$. Though the calculated decay constants for beta decay, alpha decay, and spontaneous fission for nuclides in this island are uncertain by orders of magnitude, there is a fair body of opinion[71] that the lifetime of at least one nuclide may, in its ground state, exceed $10^6$ years. In two independent calculations,[72,73] the most stable nuclide was found to have $Z=110$, $A=294$, and a half-life greater than $10^8$ years. The doubly magic nuclide, $Z=114$, $A=298$, was calculated to be $\beta$-stable and to have a longer spontaneous fission lifetime but a much shorter $\alpha$ decay lifetime, with an overall half-life of ~1 year. All nuclides with $Z<110$ were calculated to have very short half-lives. Time dilation increases the observed half-life of a relativistic nuclide by its Lorentz factor, but the flux of cosmic rays with energy greater than $\gamma Mc^2$ decreases as $\gamma^{-1.5}$, so that it would be unlikely for a nuclide with a half-life in its rest frame less than ~$10^5$ years to survive in the cosmic rays.

Some theorists feel it is unlikely that, in the conventional $r$ process, heavy nuclides capturing neutrons and moving upward in $A$ along a path to the neutron-rich side of the beta-stability line can avoid fission until they reach the island of stability.[71] Even so, it is possible that superheavy elements might be synthesized in a low-temperature decompression of neutron-star matter by following a path near the neutron drip line where the fission barrier remains above zero.[74] The calculations involve large extrapolations and are quite uncertain. The issue must in the end be decided experimentally. Experiments with heavy-ion accelerators at Berkeley and Dubna have been unsuccessful in producing superheavy elements, but attempts are continuing. The interested reader should consult Ref. 71 for recent papers on the subject of superheavy elements.

Anders and co-workers[75] have isolated rare phases in certain meteorites that contain traces of xenon gas with a peculiar isotopic composition. They have interpreted the isotopic distribution as evidence for *in situ* decay by spontaneous fission of small quantities of a superheavy element and have attempted to characterize its chemistry. The interpretation is bold and not without its critics. Blake *et al.*[76] showed that if this indirect evidence is correct, the relative abundance of superheavy elements in the cosmic rays can be estimated, provided several assumptions are made. They estimated an abundance ratio $(Z\geq 110)/(74\leq Z\leq 87)$ between 0.0002 and 0.006, which does not conflict with our ratio, 0.004, based on one event out of ~250 events with $74\leq Z\leq 87$ in all Lexan or emulsion experiments to date.

We conclude that an ultrarelativistic nucleus with $Z=110$ gives an acceptable fit to the Lexan data, gives a distant energy deposition in acceptable agreement with the emulsion data and substantially lower than that for nuclei with $Z/\beta=+114$, $Z\leq 96$, and $0.6\leq\beta\leq 0.84$, is predicted by theory to have a long enough lifetime $\gamma\tau$ in the laboratory frame to survive in the cosmic rays if made in astrophysical nuclear reactions, and is consistent with the existing, indirect, positive meteoritic evidence.

### F. Can the event be explained by a freak occurrence associated with one or more normal nuclei?

Several improbable scenarios have been suggested, none of which account for both the Lexan data and the emulsion data. Hodson[77] has proposed that a closely collimated jet of ~$10^4$ relativistic, singly charged particles resulting from the interaction of a primary cosmic ray with energy $\gtrsim 10^{18}$ eV in the material just above the first Lexan detector might account for the data. We will disregard the fact that the flux of protons of such energy is extraordinarily low and that the probability of interacting within ~1 mm of the top Lexan sheet is also quite low. We will accept Hodson's main argument that because of destructive interference, Čerenkov emission might be suppressed in a sufficiently closely collimated jet consisting of practically equal numbers of positive and negative secondaries. However, the suggestion of a jet must be rejected because it cannot account for the nearly constant etch rates throughout the Lexan stack. The possibility that a jet could produce an etchable track was quantitatively discussed ten years ago,[78] and it was shown that such a track could not exceed a few microns in length. The reason is that the spacing of the bundle of particles increases, and the ionization density decreases, with distance from the point of interaction, so that the track etch rate will decrease with depth. About half of the total number of particles in the jet will be included within an angle $\theta\approx(\gamma_{c.m.})^{-1}$, where $\gamma_{c.m.}$ is the Lorentz factor in the center-of-momentum system. For a primary energy of $10^{18}$ eV, half of the particles will emerge at angles greater than ~$2\times 10^{-5}$ rad, which in a stack of thickness ~1 cm amounts to a lateral spread greater than 2000 Å. Compared to a single particle with $Z/\beta\approx 114$, which forms an etchable track by energy deposition mainly inside a cylinder of radius $\leq$100Å, the density of radiation damage by the jet will be reduced by a factor at least $(2000/100)^2=400$ at the bottom of the stack.

Only in the top sheet of Lexan would the radiation damage density be great enough to form an etchable track.

A similar argument applies to suggestions that the particle might have been a nucleus that fissioned above the stack, a relativistic dust grain, or a relativistic molecule containing many nuclei with charges such that $\sum_i Z_i^2 \approx 114^2$. Scattering of the individual constituents would cause the track etch rate to decrease from the top to the bottom of the stack.

A nucleus that passed upward through the stack could explain the reported absence of a Čerenkov signal, because the plastic radiator film was coated only on the bottom with the fast recording film, but it could not explain the combination of data in the Lexan stack and in the three emulsions.

#### G. Future expanded searches for more particles

To allow for the possibility that the average flux of particles similar to the monopole candidate may be far lower than given by the reciprocal of the overall collecting power of Lexan/emulsion experiments to date, future searches ought to have a vastly greater collecting power. The space shuttle will eventually make it possible to expose passive arrays of detectors up to several hundred $m^2$ in area above the earth's atmosphere for times of the order of 1 year. If emulsion were used to measure the distant energy deposition, shielding or a near equatorial orbit would have to be employed to reduce the background exposure by ionizing particles in the trapped radiation belts. An array of plastic detectors, including a well-shielded emulsion array, could provide a factor $\sim 10^2$ increase in collecting power over the present value of $\sim 1$ $m^2$yr. The feasibility of such an experiment is under study.

In the summer of 1976 a colleague at Berkeley, M. Salamon, began an exposure of a 1500-$m^2$ array of Lexan detectors at a sea-level site at Lawrence Livermore Laboratory. The array consists of four layers of Lexan separated by cardboard absorbers giving a total thickness of $\sim 0.5$ g/cm$^2$, all double-bagged in waterproof plastic and covered with a light layer of gravel to prevent damage by heat, light, and wind. An analysis of the stack after a 2-year exposure would give us about a 200-fold increase in collecting power over the General Electric sea-level experiment.[60] It could not detect fast superheavy nuclei or fast antinuclei, both of which would disintegrate high in the atmosphere, but it is a relatively simple way of looking for extremely massive, electrically or magnetically charged particles that might not disintegrate and that might not produce showers or be detectable in other types of monopole experiments.

Further in the future it should be possible to build electronic arrays ten or more square meters in area that would orbit the earth for several years and record both the close energy deposition (thus giving $|Z|/\beta$) and the distant energy deposition by particles such as the one we have detected. As a specific example, instead of searching for heavy antinuclei in space with a superconducting magnet of limited area, one could use a large plastic scintillator, which responds only to the distant energy deposition,[79] together with a detector such as a gas-filled proportional counter, which responds to the total $dE/dx$, and a detector that measured velocity, such as a Čerenkov detector.

### IX. SUMMARY AND CONCLUSIONS

We have presented detailed evidence that the event in module 104, referred to for convenience as the monopole candidate, had the following two characteristics:

(1) Throughout the $\sim 1.4$ g/cm$^2$ thickness of detector stack it had a roughly constant value of $|Z|/\beta \approx 109$ to 114, derived from measurements of track etch rate, which depend on energy deposition at radial distance $\lesssim 10^{-2}$ $\mu$m.

(2) Its energy deposition at radial distance $\gtrsim 20$ $\mu$m, judged visually and photographically in the Ilford 200-$\mu$m G-5 emulsion and measured with an image dissector in two independent Kodak 10-$\mu$m NTB-3 emulsions, was consistent with that from nuclei with $Z/\beta \approx 80$ to 90 and $0.6 \lesssim \beta \lesssim 0.9$, and was incompatible with that expected from known cosmic-ray nuclei with $Z/\beta = 109$ to 114, $Z \leqslant 96$, and $0.6 \lesssim \beta \lesssim 0.84$.

If these two characteristics are accepted, calculations of energy deposition that employ the exact (Mott) nucleus-electron scattering cross section show that known cosmic-ray nuclei ($Z \leqslant 96$) are incompatible with the data, even if unlikely fragmentation sequences or effective charges are allowed. A monopole is incompatible with the data. Three classes of hypothetical particles that deposit less energy at large distances than do known nuclei with the same $|Z|/\beta = 109$ to 114 are compatible with the data:

(1) a slow, supermassive particle with $\beta \approx 0.4$, charge $\approx 45e$ and mass $> 10^3 - 10^4$ amu,

(2) a fast antinucleus with $Z/\beta \approx -109$ to $-114$ and $76 \lesssim |Z| \lesssim 96$ that might fragment with loss of one or two charges,

(3) a very fast nucleus with $Z \approx 110$ to 114 and $\beta \gtrsim 0.99$.

The particle would have been a normal nucleus only if at least one of the above two characteristics could have been rejected. Consider the two possi-

bilities:

(1) The interpretation of the Lexan data may be in error. For ultrarelativistic velocities, perhaps Lexan responds not to $Z/\beta$ but to the restricted energy loss [Eq. (2)], so that the particle might have been a nucleus with $\beta \approx 1$ and $Z \approx 90$. This is inconsistent with the evidence in Table I that the velocity dependence given by Eq. (2) does not fit the data at high $Z$ and high $\beta$, and we have pointed out that a relativistic rise in energy deposition should occur only for close collisions, not for the distant collisions that lead to chemically etchable tracks.

(2) The interpretation of the emulsion data may be in error. The low-energy deposition at large radial distances might be either *real* but due to a downward fluctuation or *apparent* and due to local regions of decreased sensitivity around the track. However, we believe that Hagstrom's Monte Carlo calculations[14] show that it is extremely unlikely that fluctuations in distant energy deposition by a normal nucleus can account for the appearance of the track in the 200-μm emulsion. Further, our calibrations of the sensitivity of individual emulsions by measurements of the optical density of Fe tracks of known $\beta$ provide evidence that the low density of silver grains around the track of the particle was not caused by an abnormally insensitive region in the 200-μm emulsion. The independent measurements of a small distant energy deposition by the particle in the two thin emulsions provide strong support for our view that neither a downward fluctuation by a normal nucleus nor a locally insensitive region of emulsion can account for the emulsion data.

We have considered several freak occurrences associated with one or more normal nuclei and find that they cannot account for the event.

Although the identity of the particle remains ambiguous, we believe the evidence for a new class of highly ionizing particles is sufficiently strong to justify intensified searches with instruments of increased collecting power.

## ACKNOWLEDGMENTS

During the prolonged investigation of this controversial event, we were sustained and encouraged by many colleagues. We are indebted for numerous ideas and valuable conversations to S. P. Ahlen, L. Alvarez, B. G. Cartwright, P. A. M. Dirac, P. H. Fowler, A. S. Goldhaber, M. Goldhaber, J. D. Jackson, E. M. McMillan, and G. H. Trilling. We wish to record our indebtedness to R. Hagstrom for the independent role he played in the analysis. We are also indebted to P. H. Fowler for hospitality and assistance in interlaboratory comparisons of photodensitometry and of ultraheavy cosmic-ray tracks in emulsions. Research at Berkeley was supported in part by ERDA under Contract No. AT (04-3)-34 and by NASA under Grant No. NGR 05-003-376; research at Houston was supported in part by NSF under Grant No. PHY 76-08374. P. B. P. thanks the Guggenheim Foundation for support and H. Sato at Research Institute for Fundamental Physics, Kyoto, and D. Hovestadt at the Max Planck Institute for Physics and Astrophysics, Garching bei Munchen, for their hospitality while much of the manuscript was written.

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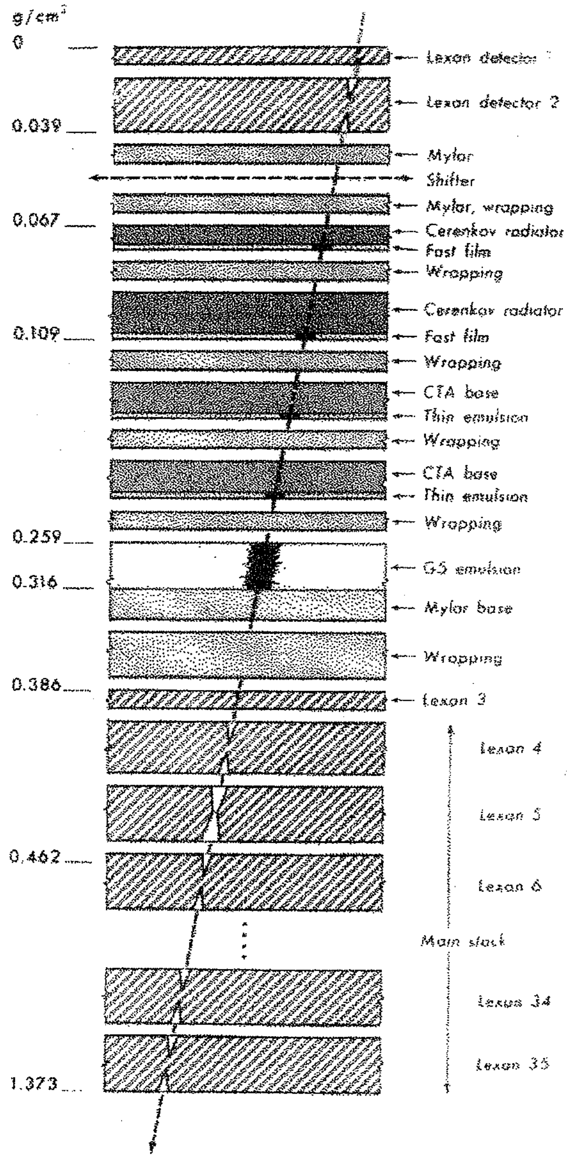


FIG. 1. Vertically expanded view of detector array with depths in g/cm² Lexan equivalent. The particle traversed the stack at a zenith angle of ~10°. Details of the wrapping and of the shifting mechanism are not shown.

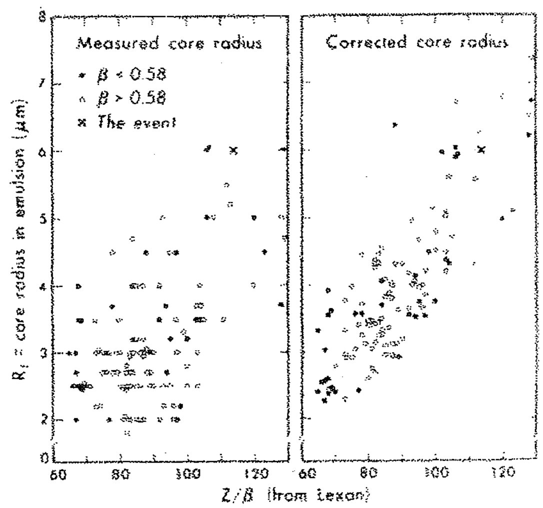


FIG. 10. Observed correlation of core radius $R_1$ with $Z/\beta$ for slow ($\beta < 0.58$) and fast ($\beta > 0.58$) particles in the Minneapolis and Sioux City flights. The point for the monopole candidate is labeled $X$. A geometric correction that takes into account distortion due to shrinkage of the emulsion gives the improved correlation shown on the right.

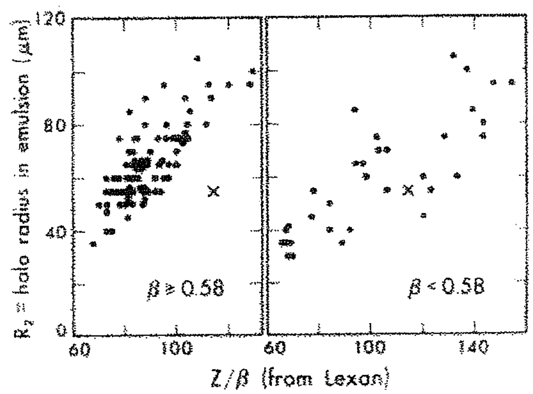


FIG. 11. Observed correlation of halo radius $R_2$ with $Z/\beta$. The halo radius for the monopole candidate, labeled $X$, is much less than expected if it were a nucleus with $\beta \geq 0.58$. The data show that slow nuclei ($\beta < 0.58$) tend to have smaller halo radii than fast nuclei with the same $Z/\beta$.

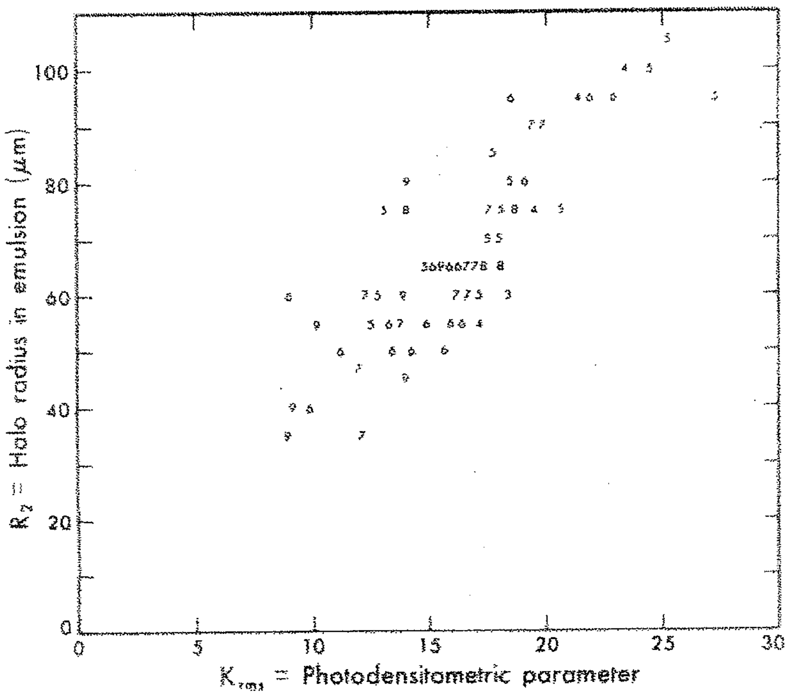


FIG. 12. Comparison of halo radius, measured visually in the G-5 emulsion, with the quantity $K_{rms}$, which is a measure of the optical density distribution determined with a photodensitometer. Each point is labeled by the value of $\beta$ truncated in tenths.

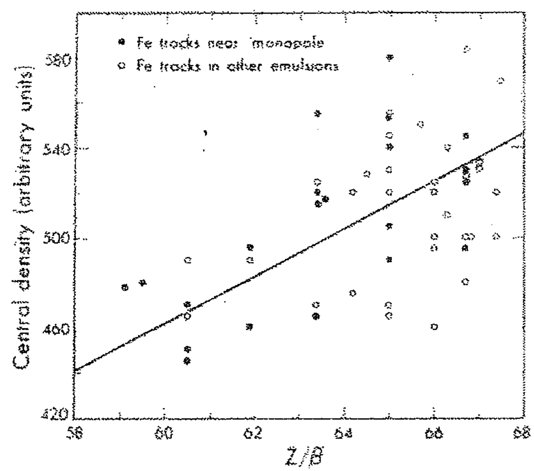


FIG. 13. Evidence that the sensitivity of the region of G-5 emulsion near the monopole candidate track was closely the same as the sensitivity of the emulsions traversed by other ultraheavy cosmic rays. The photodensitometric readings with the slit centered on the track axis show the same distribution with $Z/\beta$ for Fe tracks near the monopole-candidate track and in other emulsions.

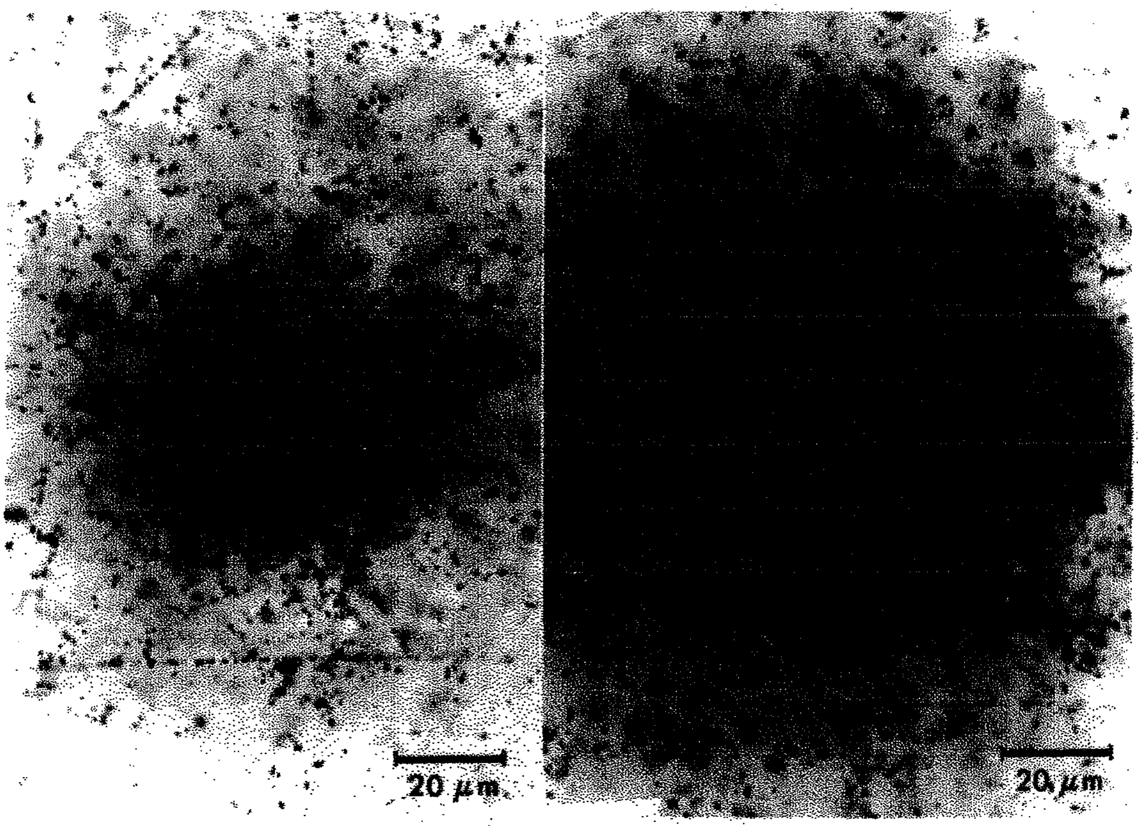


FIG. 14. Photomicrographs in G-5 emulsion of (a) the monopole-candidate track, with $Z/\beta=114$ and zenith angle $\theta=10°$, and (b) the track of a nucleus with $Z=75$, $\beta=0.67$, $Z/\beta=112$, and $\theta=14°$. For both tracks the region in focus is about one-third of the way below the top surface of the emulsion.

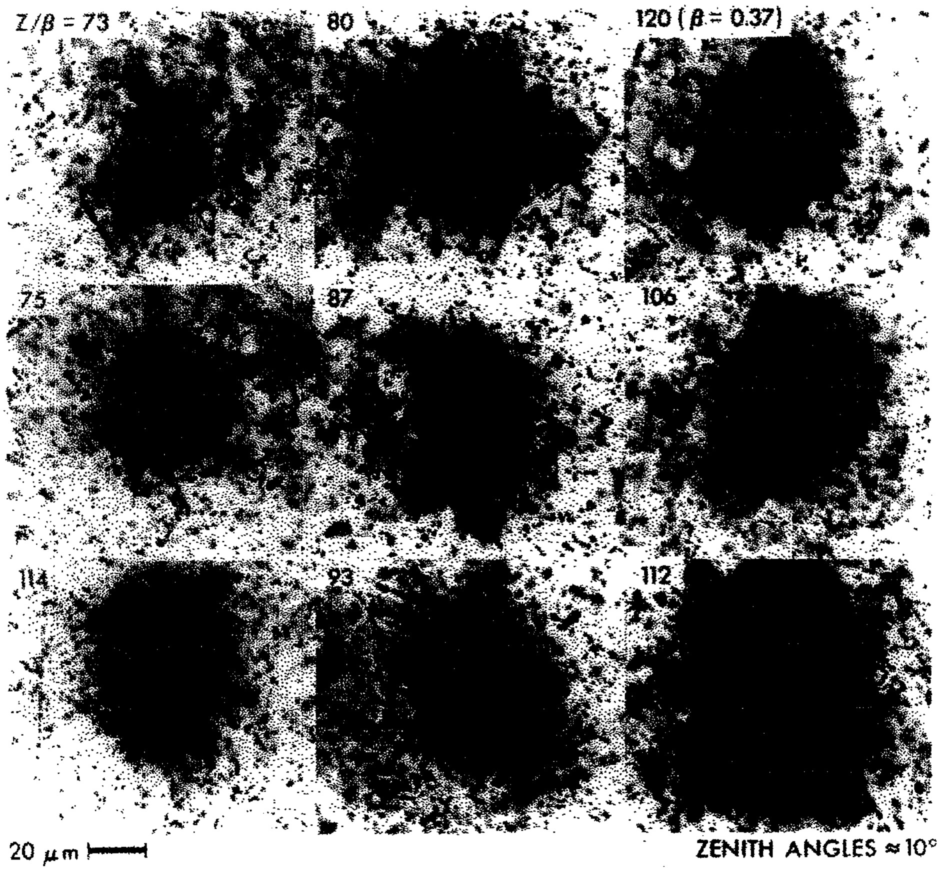


FIG. 15. Photomicrographs of tracks of the events in Table II, which have similar zenith angles and values of $Z/\beta$ ranging from 73 to 120. The abnormally small density of silver grains for the monopole-candidate track is obvious.

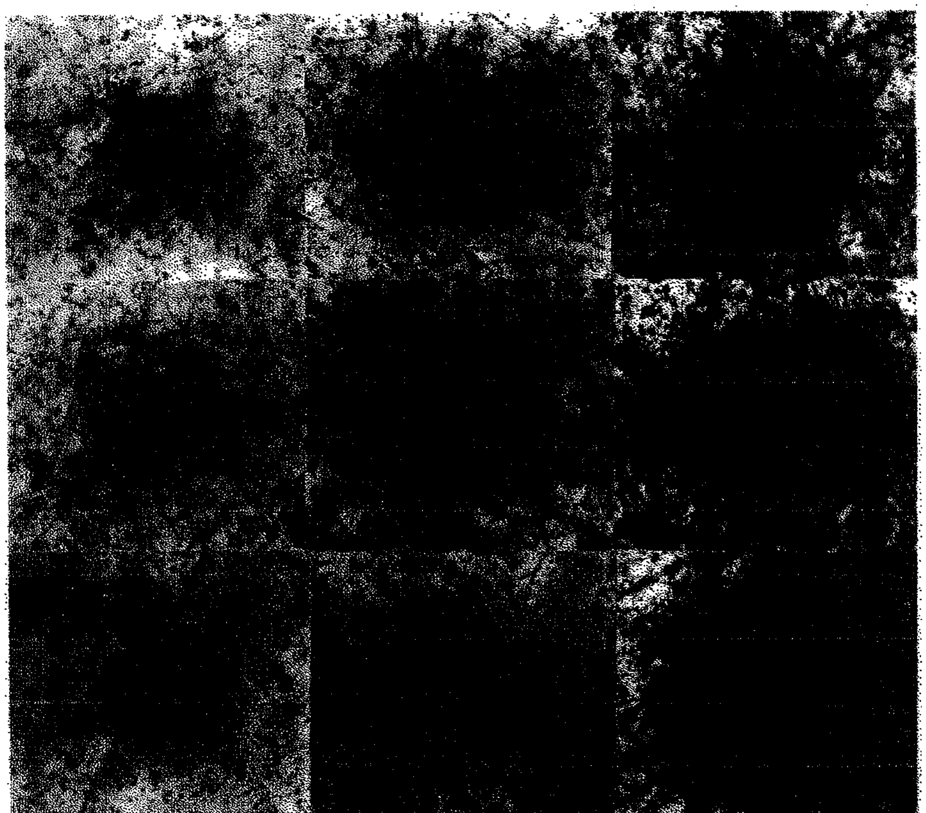

FIG. 16. Other tracks at zenith angles similar to those in Fig. 15. In the left column are tracks of particles with $Z/\beta$ between 79 and 87; in the middle column the $Z/\beta$ is between 112 and 118; in the right column $Z/\beta$ is greater than 125.

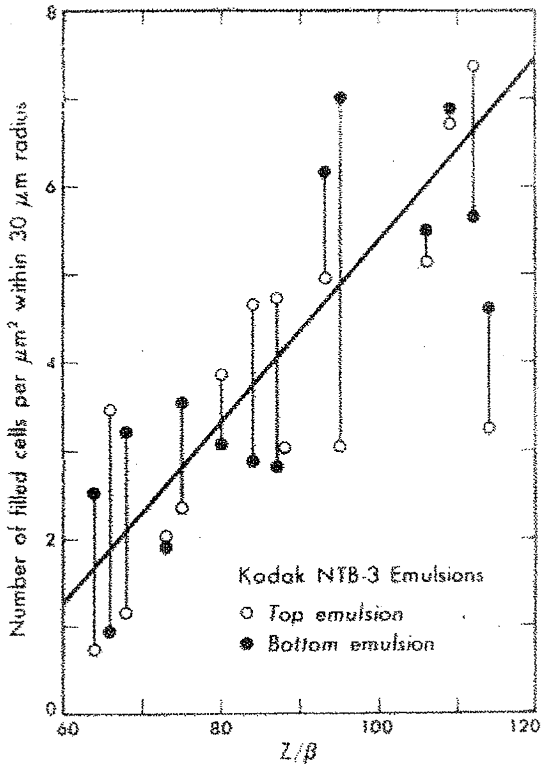


FIG. 17. Density of silver blobs in a cylinder of 30-$\mu$m radius around the track in thin emulsion as a function of $Z/\beta$ for tracks with $\theta \leq 18°$. Reproducibility of measurement at each point is better than the size of the point. In both emulsions the silver grain density for the monopole candidate (at $Z/\beta = 114$ on the graph) is much lower than expected from the least-squares line for normal nuclei.

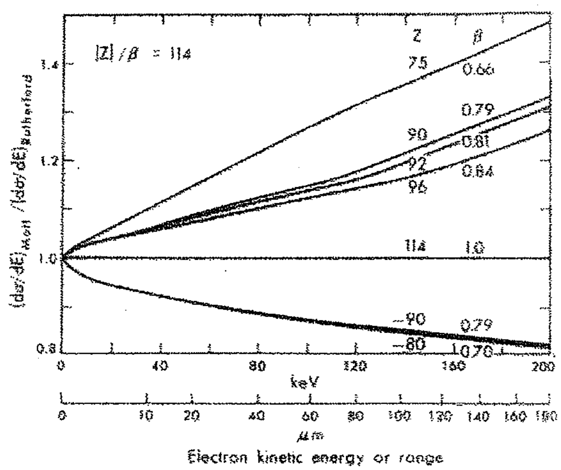

FIG. 18. Ratio of exact Mott cross section to Rutherford cross section as a function of kinetic energy or range for an electron initially at rest to be scattered by a fast nucleus or antinucleus with $|Z|/\beta = 114$. Radial-diffusion distance of an electron from a track in emulsion is much smaller than the range.

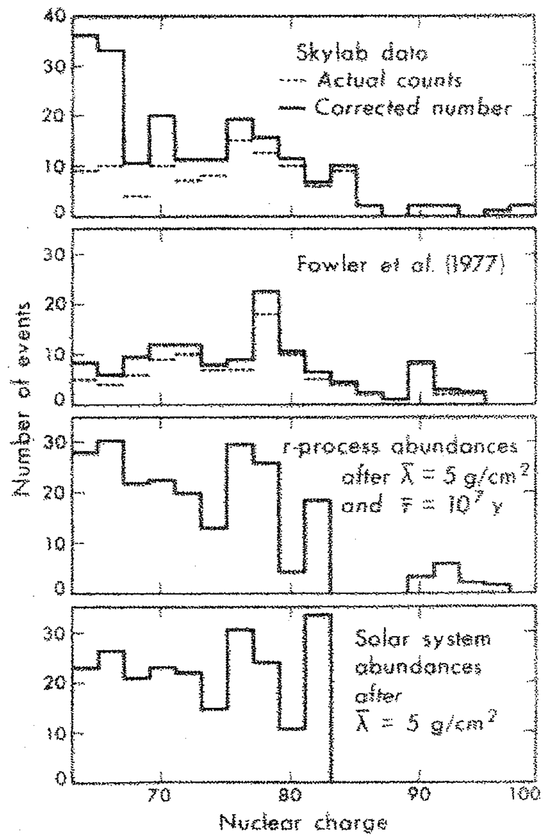


FIG. 2. Comparison of measured abundances of ultra-heavy cosmic rays with calculated abundances of material with r-process composition and with solar system composition, after distortion resulting from fragmentation and radioactive decay in interstellar space. Corrections to actual counts in top two histograms allow for detector efficiency (from Ref. 9).

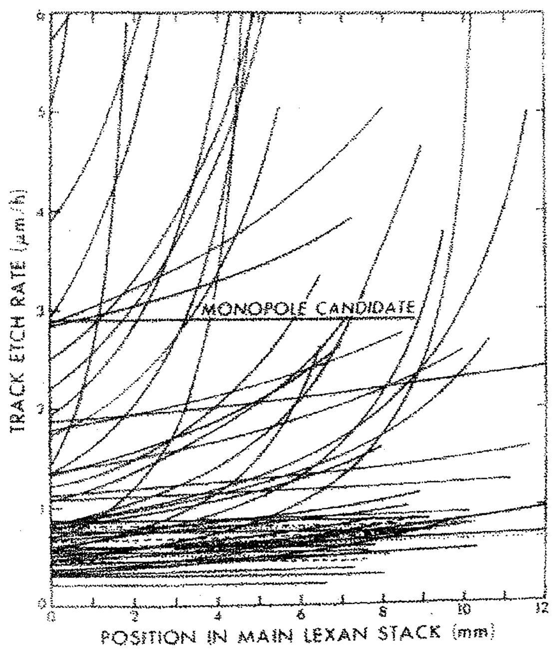


FIG. 3. Smoothed response curves for the majority of the ultraheavy particles found on the Sioux City balloon flights. A few slow particles with very steep curves are not plotted.

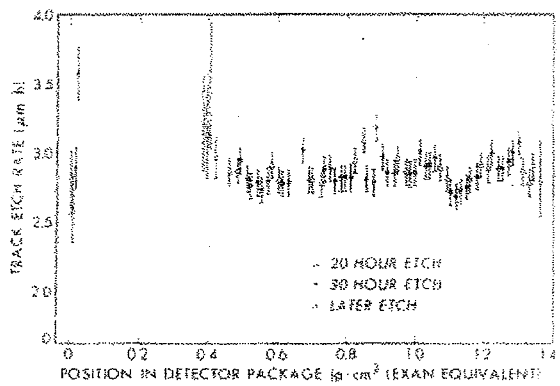


FIG. 4. Calibrated Lexan data for the monopole candidate.

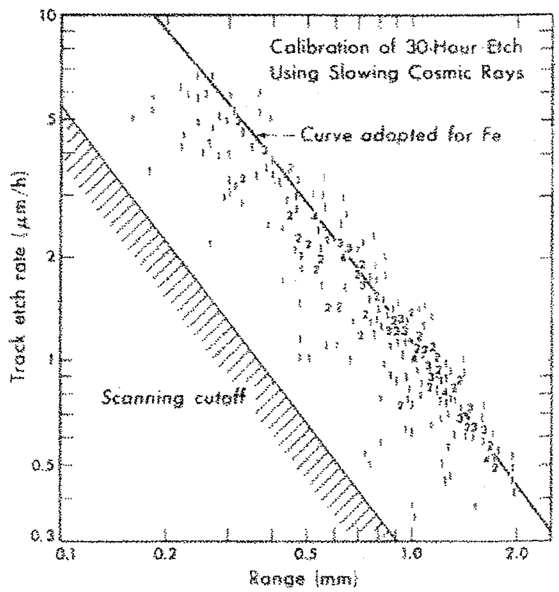


FIG. 5. Determination of the response to slowing Fe nuclei of the sheets etched 30 hours in Lexan module 104, which contained the monopole candidate.

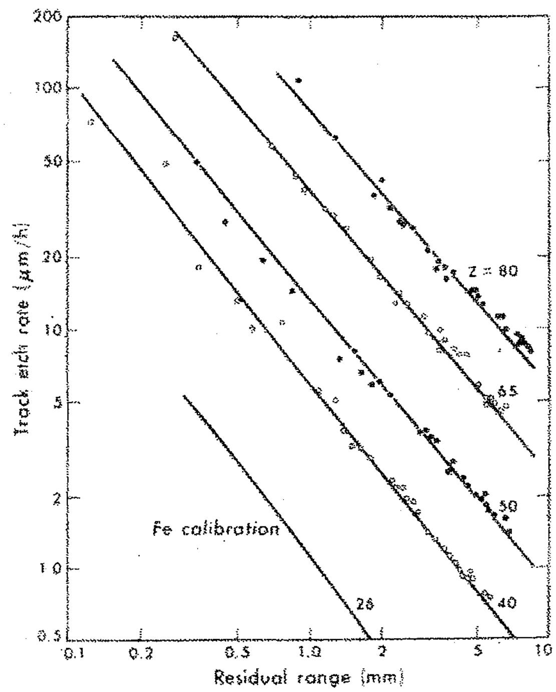


FIG. 6. Etch-rate response curves of several stopping ultraheavy nuclei as a function of residual range, along with the curve for Fe from Fig. 5. The parameters in the power-law response, Eq. (6), were determined from a fit to these data. Note that the curves of Fig. 3 become nearly straight when plotted on a log-log scale with residual range as abscissa.

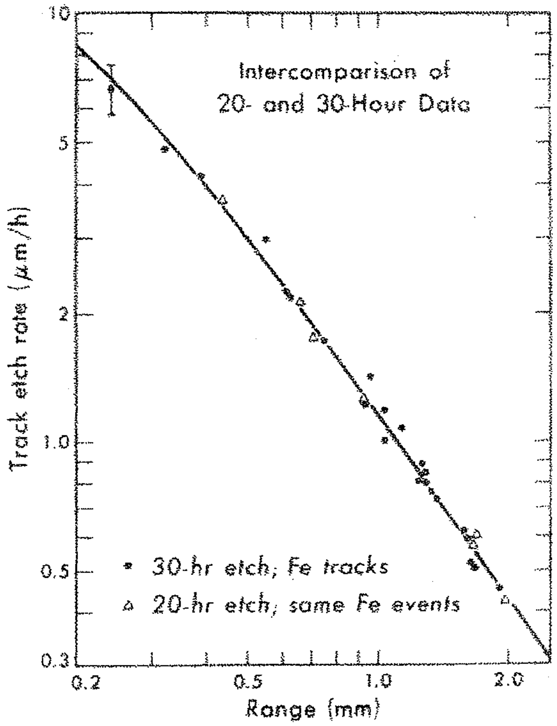


FIG. 7. Evidence that the responses of the sheets etched 20 hours and of the sheets etched 30 hours were the same (see text).

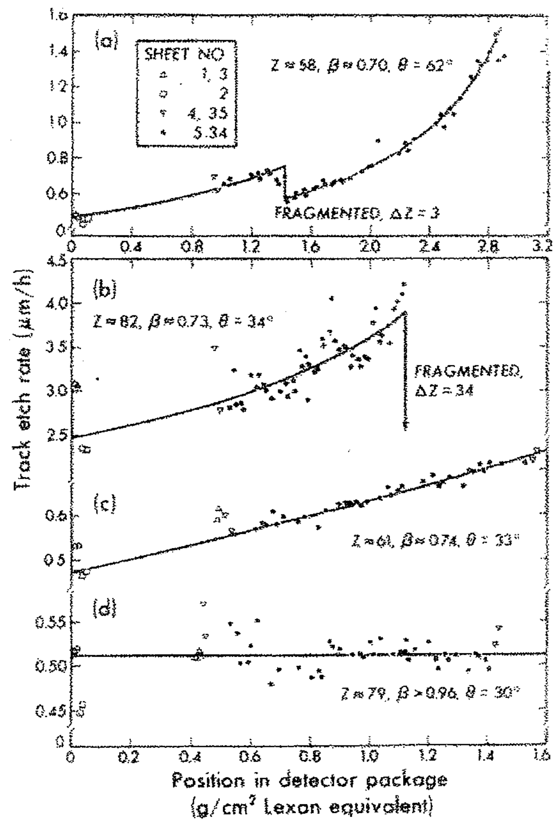


FIG. 8. Etch-rate response data for several ultraheavy nuclei, showing examples of fragmentations and small, systematic variations in response of sheets 1, 2, 3, 4, and 35.

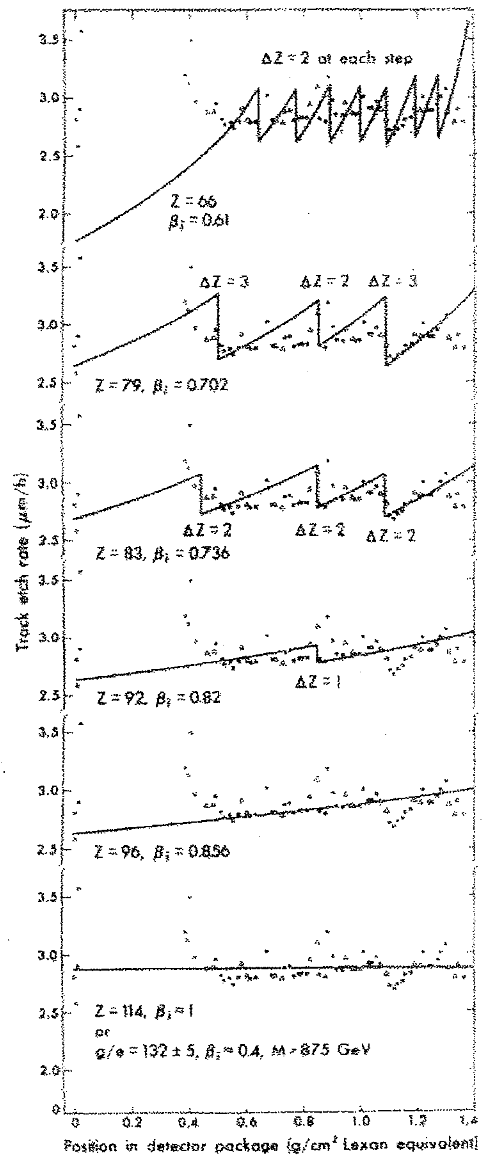


FIG. 9. Response curves for several combinations of initial $Z$ and $\beta$ and fragmentations that approximately pass through the data. If the initial $\beta$ is small, the number of successive fragmentations must be large.